# New constraint on the cosmological background of relativistic particles

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Abstract. We have derived new bounds on the relativistic energy density in the Universe from cosmic microwave background (CMB), large scale structure (LSS), and type Ia supernova (SNI-a) observations. In terms of the effective number of neutrino species a bound of  $N_{\nu} = 4.2^{+1.2}_{-1.7}$  is derived at 95% confidence. This bound is significantly stronger than previous determinations, mainly due to inclusion of new CMB and SNI-a observations. The absence of a cosmological neutrino background  $(N_{\nu} = 0)$  is now excluded at  $5.4\sigma$ . The value of  $N_{\nu}$  is compatible with the value derived from big bang nucleosynthesis considerations, marking one of the most remarkable successes of the standard cosmological model. In terms of the cosmological helium abundance, the CMB, LSS, and SNI-a observations predict a value of 0.240 < Y < 0.281.

#### 1. Introduction

From detailed observations of the cosmic microwave background (CMB) [1–8], the large scale structure (LSS) of galaxies [9–11], and distant type Ia supernovae (SNI-a) [12–14] many of the fundamental cosmological parameters are known quite precisely. Very interestingly the precision of the data is now also at a level where particle physics beyond the standard model can be probed. One of the prime examples of this is the total cosmological energy density in relativistic particles.

In the standard model photons and neutrinos are by far the largest source of entropy in the Universe (and consequently also of energy density in the early Universe), and neutrinos are therefore the largest source of entropy in non-electromagnetically interacting species.

In the early Universe neutrinos decouple at a temperature of roughly 2-3 MeV. Shortly after this, electrons and positrons annihilate and transfer entropy to the photons. The end result is that the temperature of neutrinos is roughly  $(4/11)^{1/3}T_{\gamma}$ . The total energy density in weakly interacting relativistic species is therefore  $\rho_{\nu} \sim 3(4/11)^{4/3}\rho_{\gamma} \sim 0.78\rho_{\gamma}$ .

Any additional relativistic energy density can be thought of as additional neutrinos, and from the perspective of late time evolution after neutrino decoupling it is customary to parameterize any such additional energy density in terms of  $N_{\nu}$  [15], the equivalent number of neutrino species

$$N_{\nu} = \frac{\rho}{\rho_{\nu,0}},\tag{1}$$

where  $\rho_{\nu,0}$  is the density in a massless standard model neutrino species which has a temperature of exactly  $(4/11)^{1/3}T_{\gamma}$ . The value predicted by the standard model is actually  $N_{\nu} = 3.04$  because of finite-temperature QED effects and incomplete neutrino decoupling (see for instance [17] for a review or [18] for a very recent study).

In general, a species, X, decoupling from thermal equilibrium while relativistic contributes an  $N_{\nu,X}$  given by (see for instance [16])

$$N_{\nu,X} = g_X \left(\frac{10.75}{g_{*,D}}\right)^{4/3} \times \begin{cases} 1 \text{ (fermions)} \\ \frac{8}{7} \text{ (bosons)} \end{cases}, \tag{2}$$

where  $g_X$  is the number of helicity states of the species and  $g_{*,D}$  is the effective number of degrees of freedom in the plasma at the time of X-decoupling.

In the present paper we calculate cosmological constraints on  $N_{\nu}$  from presently available data. In the past the main source for constraints on  $N_{\nu}$  has been big bang nucleosynthesis (BBN). However, recently observations of the CMB, LSS, and distant type Ia supernovae have reached a precision where they can be used to constrain  $N_{\nu}$  at a competitive level [19–30]. Here we perform a detailed and updated calculation of CMB, LSS, and SNI-a constraints on  $N_{\nu}$  and compare them with present BBN constraints. In Section 2 we discuss present observational constraints, and section 3 contains a discussion.

parameter	prior	
$\Omega = \Omega_m + \Omega_{\rm DE} + \Omega_{\nu}$	1	Fixed
h	$0.72 \pm 0.08$	Gaussian [36]
$\Omega_b h^2$	0.014 – 0.040	Top hat
$m_ u$	$0-5~{\rm eV}$	Top hat
$w_{ m DE}$	-2.50.5	Top hat
$n_s$	0.6 – 1.4	Top hat
au	0 - 1	Top hat
Q		Free
b	_	Free

**Table 1.** The different priors on parameters used in the likelihood analysis.

#### 2. Current constraints

Using the presently available precision data we have performed a likelihood analysis for the relativistic energy density, parameterized in units of the effective number of neutrino species,  $N_{\nu}$ . We assume the relativistic energy density to be distributed in  $N_{\nu}$  light Majorana fermion species, each with mass  $m_{\nu}$ . The standard case with 3 very light neutrino species plus possible additional relativistic species just corresponds to taking  $m_{\nu} \to 0$ . The reason why  $m_{\nu}$  is allowed to be different from 0 is that there is a well-known degeneracy between  $m_{\nu}$  and  $N_{\nu}$  in CMB and LSS data [25, 29, 30].

As our framework we choose a flat dark energy model with the following free parameters:  $\Omega_m$ , the matter density, the curvature parameter,  $\Omega_b$ , the baryon density, w, the dark energy equation of state,  $H_0$ , the Hubble parameter,  $n_s$ , the spectral index of the initial power spectrum, and  $\tau$ , the optical depth to reionization. The normalization of both CMB and LSS spectra are taken to be free and unrelated parameters. The dark energy density is given by the flatness condition  $\Omega_{\rm DE} = 1 - \Omega_m - \Omega_{\nu}$ .

The priors we use are given in Table 1. The prior on the Hubble constant comes from the HST Hubble key project value of  $h_0 = 0.72 \pm 0.08$  [36], where  $h_0 = H_0/100 \,\mathrm{km}\,\mathrm{s}^{-1}\,\mathrm{Mpc}^{-1}$ .

Likelihoods are calculated from  $\chi^2$  so that in 2-dimensional plots the 68% and 95% regions are formally defined by  $\Delta\chi^2=2.30$  and 6.17 respectively. Note that this means that the 68% and 95% contours are not necessarily equivalent to the same confidence level for single parameter estimates. In 1-dimensional plots the same formal confidence levels are given by  $\Delta\chi^2=1$  and 4.

#### 2.1. Type Ia supernovae (SNI-a).

We perform our likelihood analysis using the "gold" dataset compiled and described in Riess et al [14] consisting of 157 supernovae using a modified version of the SNOC package [35].

#### 2.2. Large Scale Structure (LSS).

Any large scale structure survey measures the correlation function between galaxies. In the linear regime where fluctuations are Gaussian the fluctuations can be described by the galaxy-galaxy power spectrum alone,  $P(k) = |\delta_{k,gg}|^2$ . In general the the galaxy-galaxy power spectrum is related to the matter power spectrum via a bias parameter,  $b^2 \equiv P_{gg}/P_m$ . In the linear regime, the bias parameter is approximately constant, so up to a normalization constant  $P_{gg}$  does measure the matter power spectrum.

At present there are two large galaxy surveys of comparable size, the Sloan Digital Sky Survey (SDSS) [9, 10] and the 2dFGRS (2 degree Field Galaxy Redshift Survey) [11]. Once the SDSS is completed in 2005 it will be significantly larger and more accurate than the 2dFGRS. In the present analysis we use data from both surveys. In the data analysis we use only data points on scales larger than k = 0.15h/Mpc in order to avoid problems with non-linearity.

## 2.3. Cosmic Microwave Background (CMB).

The temperature fluctuations are conveniently described in terms of the spherical harmonics power spectrum  $C_{T,l} \equiv \langle |a_{lm}|^2 \rangle$ , where  $\frac{\Delta T}{T}(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi)$ . Since Thomson scattering polarizes light, there are also power spectra coming from the polarization. The polarization can be divided into a curl-free (E) and a curl (B) component, yielding four independent power spectra:  $C_{T,l}$ ,  $C_{E,l}$ ,  $C_{B,l}$ , and the T-E cross-correlation  $C_{TE,l}$ .

The WMAP experiment has reported data on  $C_{T,l}$  and  $C_{TE,l}$  as described in Refs. [1–5]. We have performed our likelihood analysis using the prescription given by the WMAP collaboration [1–5] which includes the correlation between different  $C_l$ 's. Foreground contamination has already been subtracted from their published data.

We furthermore use the newly published results from the Boomerang experiment [6–8] which has measured significantly smaller scales than WMAP.

#### 2.4. Results

In Fig. 1 we show the results of the likelihood analysis for all the currently available data. As with previous analyses which include WMAP data the best fit is higher than  $N_{\nu}=3$ , but with  $N_{\nu}=3$  well within the 95% contour. In terms of  $N_{\nu}$  the formal allowed region is

$$N_{\nu} = 4.2^{+1.2}_{-1.7} (95\% \text{ C.L.}).$$
 (3)

This can be compared with the previous limit of [30]

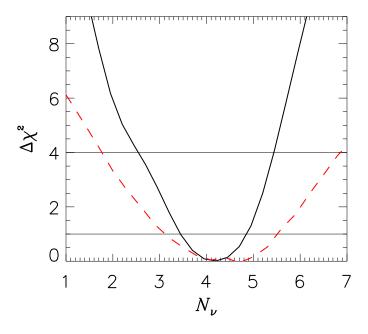
$$1.6 < N_{\nu} < 7.2 \text{ (95\% C.L.)}.$$
 (4)

It is quite interesting to compare these limits. The parameter space used in the present analysis is larger (taking w as a free parameter), but also uses newer data (the Riess et al. SNI-a data and the Boomerang data). The new data significantly strengthens

the constraint and clearly the severe degeneracy between w and  $m_{\nu}$  which affects the neutrino mass bound [31] has no significant impact on the determination of  $N_{\nu}$ .

Interestingly the value  $N_{\nu} = 0$  is excluded at 5.4 $\sigma$ , confirming the presence of a cosmological background of relativistic particles. However, at present observations are not precise enough to determine the exact nature of the relativistic background, such as whether it is of fermionic or bosonic nature. Other studies have shown that the relativistic background must be weakly interacting around the epoch of recombination [32,33]. At present all observations are therefore compatible with standard model neutrinos as the only non-electromagnetically interacting relativistic background, but cannot definitively rule out a background of other light particles.

In order to compare with the previous analysis, we also show  $\chi^2$  for an analysis with only WMAP and LSS data, but keeping  $m_{\nu}=0$ . The 95% allowed region is in that case 1.7 <  $N_{\nu}$  < 6.9, in very good agreement with Fig. 2b in [30]. Fig. 1 shows the quite significant improvement from including the new Boomerang and SNI-a data.



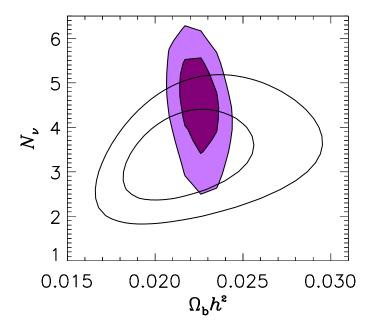
**Figure 1.**  $\Delta \chi^2$  values as a function of  $N_{\nu}$  for various data sets. The full line includes all available data, and the dashed line is for WMAP and LSS data only.

#### 2.5. Comparison with Big Bang Nucleosynthesis

The other main probe of relativistic energy density in the early Universe is big bang nucleosynthesis (BBN). It is therefore highly interesting to compare the BBN inferred values of  $\Omega_b h^2$  and  $N_{\nu}$  in order to check consistency.

At present the measured primordial helium-4 abundance is quite uncertain (see for instance [37] for a recent discussion). One of the most recent determinations is [38, 39]

$$Y = 0.2495 \pm 0.0092,\tag{5}$$



**Figure 2.** The 68% (dark) and 95% (light) likelihood contours for  $\Omega_b h^2$  and  $N_{\nu}$  for all available data. The other contours are 68% and 95% regions for BBN, assuming the <sup>4</sup>He and D values given in [39].

where Y is the <sup>4</sup>He mass fraction. However, the systematic uncertainty in the measurement is almost certainly larger than this.

The primordial deuterium fraction is fairly well measured in high redshift absorption systems. We use the value [39] ‡.

$$\frac{D}{H} = (2.78 \pm 0.29) \times 10^{-5}. (6)$$

Based on these values we have calculated the allowed region in  $\Omega_b h^2$ ,  $N_{\nu}$  space. The result is shown in Fig. 2. The BBN determination is clearly compatible with the CMB+LSS+SNI-a determination. Very interestingly the uncertainty in  $N_{\nu}$  from CMB+LSS+SNI-a is now comparable to what can be obtained from BBN. Using the <sup>4</sup>He and D abundances quoted above Cyburt et al. [39] find that  $N_{\nu} = 3.14^{+0.7}_{-0.65}$  at 68% C.L. This yields a 95% bound on  $\Delta N_{\nu}$  of roughly 1.4, comparable to the present bound from CMB, LSS, SNI-a.

# 2.6. What are the predictions for primordial <sup>4</sup>He?

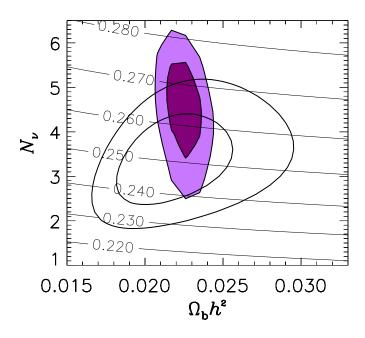
Given the stringent constraint on  $\Omega_b h^2$  and  $N_{\nu}$  from CMB, LSS, and SNI-a data, it is worthwhile to consider the bound on the primordial <sup>4</sup>He value which can be derived from these data. At 95% C.L. the bound is

$$0.240 < Y < 0.281. (7)$$

‡ Note that one very recent study found a significantly lower value of  $D/H = 1.6^{+0.25}_{-0.30} \times 10^{-5}$  [40]. Evidently the uncertainty in the primordial deuterium abundance may also have been underestimated.

This is entirely compatible with the value  $Y=0.2495\pm0.0092$  recently derived. However, the allowed region is significantly larger than the value of  $Y=0.238\pm0.005$  suggested a few years ago based on a large sample of low-metallicity systems [41]. In Fig. 3 we show isocontours for <sup>4</sup>He as a function of  $\Omega_b h^2$  and  $N_\nu$  overlayed on the likelihood analyses.

It should be noted that the allowed region is much larger than the value quoted in [42],  $Y = 0.2485 \pm 0.0005$  (in a comparable study [43] found  $Y = 0.2481 \pm 0.0002$  [stat]  $\pm 0.0004$  [syst], assuming  $\Omega_b h^2 = 0.023$ .). The reason is that this assumes a fixed value of  $N_{\nu} = 3$  and therefore only applies if light, standard model neutrinos is the only source of relativistic energy.



**Figure 3.** Isocontours for Y as a function of  $\Omega_b h^2$  and  $N_{\nu}$ . The likelihood contours are as in Fig. 2.

Because the primordial Helium abundance has a direct influence on recombination it is in principle also possible to measure Y from CMB data alone. However, at present the bound is not competitive ([44] found a presently allowed range of 0.160 < Y < 0.501 at 68% C.L.). With future data the helium determination from CMB alone will improve significantly and allow for one more important consistency check between BBN and CMB.

#### 3. Discussion

We have calculated updated constraints on the cosmological background of relativistic particles from CMB, LSS, and SNI-a. In the present analysis, a larger set of cosmological parameters has been used, as well as new CMB and SNI-a data. We find, at the 95% C.L. that the bound on the relativistic energy density in terms of the effective number

of neutrino species is  $N_{\nu} = 4.2^{+1.2}_{-1.7}$ . The precision of this bound is now comparable to, or better than, what can be found from big bang nucleosynthesis considerations. Furthermore, the systematic uncertainties plaguing the determination of the primordial helium determination makes any exact BBN bound hard to obtain.

The present data also shows evidence for a cosmological background of weakly interacting, relativistic energy density at the  $5.4\sigma$  level, an important confirmation of the standard cosmological model.

The uncertainty in  $\Delta N_{\nu}$  has decreased from roughly 10 five years [19] ago to about 1.5 at present, an impressive improvement on a very short timescale. Within the next five years the measurement of  $N_{\nu}$  from CMB data alone could reach the 0.1 precision level [45, 46], indicating an improvement by two orders of magnitude in the span of a decade.

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